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A Common ATC Constraints Model for Trajectory Prediction.

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Summary

This document presents the results of a short study into a common ATC constraints model for trajectory prediction that has been performed under EEC project reference `ERS-3-BD`. The study has consisted of three parts. The first part covered the preparation and conduct of a workshop on this issue with participation of various experts from EUROCONTROL. In the second part of the study the results of the workshop were studied and complemented with an expert analysis of the topic. One of the main focuses has been to identify issues for further research and development that will contribute to a common understanding of constraints and trajectories. In parallel with the second part of the study, the third part has concentrated on updating the EUROCONTROL document " ESCAPE, User/Software Requirements Document ATC Constraints, V1.0, EEC, 9 July 1998."

The result of the study can be summarised by the conclusion that the notion of constraints is not a simple one. It is tightly linked to the organisation and concept of the whole ATM process. Each part of the ATM process can be associated with its own set and types of constraints. There is also a lot of history present in current day ATC constraints. New ATM concepts can only be successfully introduced when a thorough understanding of the current operations exists, including the role of constraints in ATM.

Contents

(44 pages in total)

1 Introduction

1.1 Objective

In several Air Traffic Management developments over the past years the awareness of the use of so-called 'constraints[1]' has grown. These constraints can impair the routes and/or profiles that aircraft will follow. Accurate knowledge of applicable constraints will allow ATC operational staff and systems to predict which trajectory a particular flight will follow. A very clear example of such developments can be seen in the Programme for Harmonised ATM Research in EUROCONTROL (PHARE) that ran from 1989 until 1999. In the operational concept developed in this programme, controllers were given system support to manipulate constraints that would be used to predict future aircraft trajectories. Constraints would even be exchanged with the airborne systems so that each flight could optimise its own trajectory subject to these constraints. Other projects and programmes, both in Europe and in the U.S. have addressed similar notions of constraints.

For structuring further activities related to the notion of constraints the EUROCONTROL Experimental Centre (EEC) has identified the need to create a comprehensive overview of what is meant by constraints and how they can be used in generating aircraft trajectories for use in ATM. The current document presents this overview.
In addition to generating this overview there is a subsidiary objective to review and adjust the "ESCAPE User/Software Requirements Document ATC Constraints" (ref. [3]). In this process, the document will also be converted to a more standard electronic format.

1.2 Approach

After having collected existing material on the topic of constraints, a kick-off meeting with the EUROCONTROL project responsible has taken place, in which, amongst others, agreement was reached on the scope and direction of the study.

With the basic material collected, the next activity has been to prepare and run a workshop. The set-up and execution of the workshop were performed in close co-operation with the EEC co-ordinator. The uninterpreted workshop results are presented in Appendix A.

These workshop results and the outcome of the initial survey have subsequently been interpreted and are presented in this document. An analysis is given of the role of constraints in ATM and especially in relation to trajectory modelling, now and in the medium term future.

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1 Whereas the contract for this study mentions the term 'ATC Constraints' it has been decided to use the general term 'constraints' as much as possible throughout this document. From the study it has become clear that various types of constraints can exist and that the term 'ATC Constraints' may lead to false or limited interpretations.

Some issues regarding general system requirements and human machine interface issues are described as well.
The work is concluded with suggestions for further developments that can facilitate the structured operational use of ATC constraints in the future.

1.3 Scope

This document presents the results of the study on ATC constraints. In an annex, the results of the workshop that was organised are presented. The main text covers a view of how constraints relate to ATM in general and to trajectory modelling in particular. It also covers an analysis of issues where further development is needed.

1.4 Structure

The document follows a simple structure. Whereas the results of the workshop have been placed in Appendix A, its interpretation is integrated in chapter 2 with the analysis of constraints. The analysis starts with a proposal for a general definition of a constraint. This is followed by an overview of the operational use of constraints and their impact on trajectories. Subsequently the predictability of trajectories is addressed followed by the foreseen changes that could be introduced by new ATM concepts currently being developed. Two conceptual developments (ground based 4D ATM and free flight) are described in some detail. The analysis is concluded with a high level view on the relationship between the human and system perspectives of trajectories and constraints.
In chapter 3 conclusions are presented followed by recommendations in chapter 4.

Note: whenever in this document reference is made to a person, it is intended to avoid any bias towards men or women. In order to improve readability it has however been decided not to use phrases like “his/her” or “ (s)he” but only use the male forms.

In a separate document an update is provided of the document " ESCAPE, User/Software Requirements Document ATC Constraints".

2 Analysis

2.1 What are constraints

In order to make sure that throughout this document a consistent view on constraints is used this section starts by defining what constraints are considered to be and how they came about.

Probably less than a decade after the Wright brothers made the first powered flight in history it was realised that if air transport was not properly managed aircraft might hit each other in the air. From then on Air Traffic Control (ATC) gradually took shape. With its task of providing a safe and expeditious flow of air traffic, ATC is constraining individual flights for the benefit of the whole. As was pointed out at the workshop (see Appendix A) that was organised on this topic, constraints are thus intrinsically connected to providing an ATC service.

Over the decades the services provided to air traffic have grown and become more complex. Nowadays we normally speak of Air Traffic Management (ATM) as a collection of services of which Air Space Management (ASM), Air Traffic Flow Management (ATFM) and Air Traffic Control (ATC) most directly affect the actual flights. Since each of these services has its own scope and objective they each affect flights in its own specific way.

When trying to come to a common interpretation of ‘constraint’ one is easily drawn in views that relate to previous activities in which one has been involved. In other words, everyone’s interpretation of the meaning of ‘constraint’ is determined by his own background and experience. In general terms however a definition of constraint could look as follows:

> A constraint is a rule that may limit the trajectory followed by a flight in one or more dimensions.

It will be clear that this is a very general definition. It leaves open several questions like:

- Who defines a constraint?
- When are constraints defined?
- Is a constraint applicable to a single flight, to a predefined selection of flights or to any flight that meets a particular condition?
- What is the life span of a constraint?
- Can a flight be subject to several constraints?
- Can constraints be prioritised?
- What happens if a constraint is not, or can not be met?

The remainder of this document is intended to shed a light on these questions and generate a common understanding of the issues involved.

2.2 Operational purpose of constraints

Through the set-up of the workshop, it has been tried not to limit the interpretation of ‘constraint’ to a particular type. Based on a discussion of what an unconstrained flight would mean it has been tried to assess the various sources and types of constraints. The idea has been to relate these constraint types to the various services within ATM, viz. ASM, ATFM and ATC. Each of these services has been defined with the idea of organising a particular aspect of air traffic. The nature of each service plays an important role in the types of constraints that it brings forward.

Air Space Management (ASM) is involved with the organisation of the overall airspace to make it available for all users on the basis of equity. In this role the service is responsible for defining which piece of airspace will be designated for which use and which rules will apply to this use. Various categories of airspace are defined (with ICAO standards as the basis, but with national variations) that are related to the ATC service that will be provided and that also constrain the execution of certain types of flights (e.g. to limit the maximum speed of traffic while operating below a certain level). ASM is also tasked with the definition of the route structure on which General Air Traffic (GAT) will normally operate. This route structure, with all its associated elements like SIDs, STARs, Conditional Routes (CDRs), available flight levels etc., is probably the most prominent ‘ASM constraint’ put on air traffic in general.
In the current ATM organisation ASM is mostly a long-term strategic activity (it is not concerned with particular individual flights). Constraints resulting from ASM are therefore also mostly of strategic nature.

Air Traffic Flow Management (ATFM) is involved with the planning of traffic flows in such a way that the available ATC capacity will not be exceeded. In Europe, this is achieved mostly at a medium term strategic level (concerning individual flights in their planning phase) by the Central Flow Management Unit (CFMU). The CFMU can assign departure time slots to flights. Such an ‘ATFM Constraint’ will only affect the time dimension of the executed trajectory. In certain conditions ATFM may also constrain the usage of certain routes in order to prevent flights from planning through a busy area.
It should be noted that ATFM works in a framework defined by ASM.

Air Traffic Control is responsible for maintaining a safe and expeditious flow of air traffic. For maintaining separation between individual flights, ATC will apply constraints tactically, usually by giving R/T instructions. Since the ATC process is performed in a 'distributed centralised' nature, i.e. control responsibility centralised in a number of ATC Centres (ATCC) each serving a number of airspace sectors, there exists a need for co-ordination the activities between these sectors. Within the framework defined by ASM, this is implemented by operating procedures and Letters of Agreement (LoA). While operating procedures define a/o the handling of air traffic between sectors within an ATCC, LoAs do the same between ATCCs. Both operating procedures and LoAs will influence the individual air traffic controllers in their control of traffic. As such they have a constraining effect on flights and they should thus also be considered as constraints. It should be noted that the EEC USRD document on ATC constraints [3] that has been reviewed and updated as part of this study deals only with this type of constraints. Its scope is thus far more limited than this report.

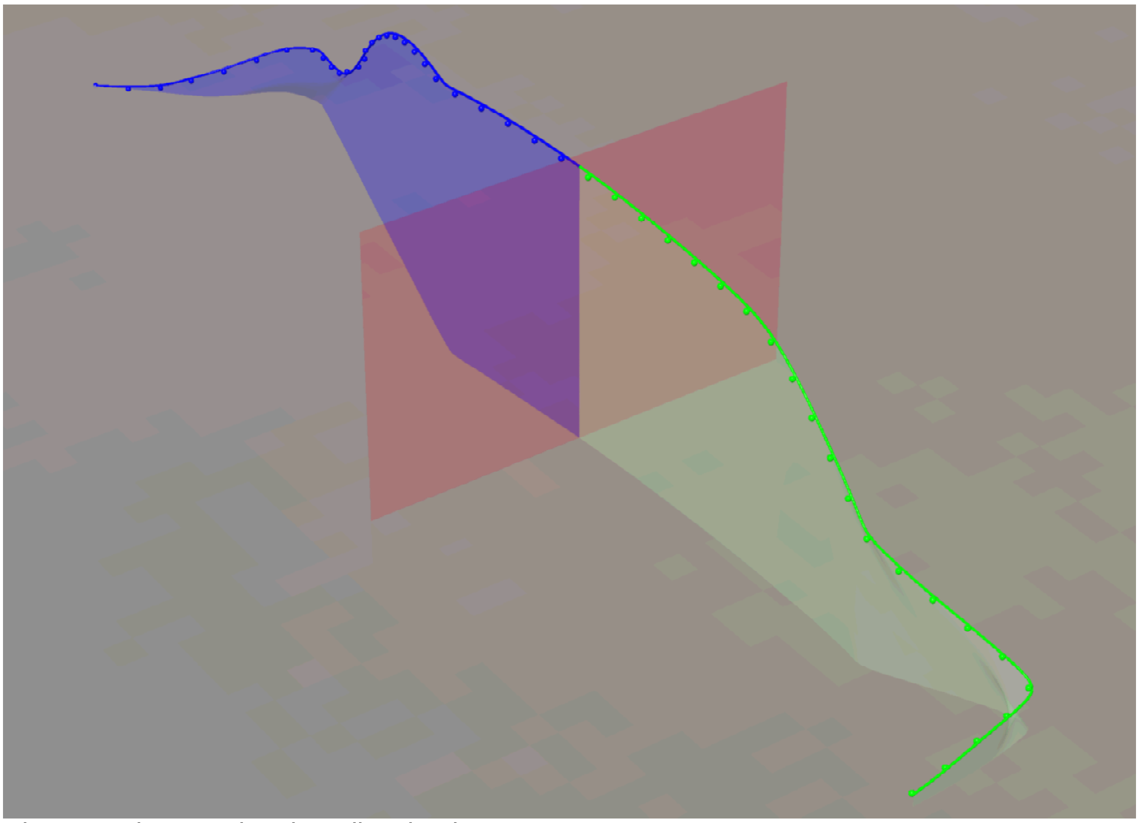

Figure 1: The actual and predicted trajectory.
(The green curve represents the 'Actual Trajectory'. It ends at the current position (represented by the red plane). The blue remainder trajectory represents a 'Predicted Trajectory' and starts at the current position.)

2.3 Constraints' impact on trajectories

Now that a general definition of constraints has been given and the operational purpose of constraints has been illustrated, an overview will be presented of the impact that constraints can have on flight trajectories.

Of course, we first need a view on what a trajectory is. From ref. [12] the following definition is taken:

> A trajectory is a representation of the path of an aircraft, describing the horizontal and vertical profile over time.

Typically, a trajectory can thus be represented by a sequence of 4-D points. The points may be annotated to allow for links to additional information (e.g. identifying sector entries/exits or flight phase information).
The *'actual trajectory'* of a flight will only represent the path that has been flown up to the current position. A *'predicted trajectory'* represents the path that an aircraft is expected to follow from its current position onwards as derived from a set of input data and assumptions (see Figure 1). As will be further elaborated in section 2.5 there may exist several different versions of both the actual and predicted trajectory of a particular flight (in particular different 'ATM actors' may generate their own predicted trajectories). For the remainder of this document, the term trajectory will refer to a predicted trajectory unless otherwise indicated.

The way in which the various types of constraints finally affect actual trajectories requires particular attention. The actual trajectory is determined on board the aircraft. A modern, commercially operated, aircraft will normally be fitted with a Flight Management System (FMS). The FMS will be programmed to contain an electronic version of the flight plan together with other data related to aircraft performance, operator preferences and a meteorological forecast. In combination with position and state information, the FMS will guide the aircraft to meet its predicted trajectory[2]. Some types of constraints will be integrated in the flight plan that is programmed in the FMS (e.g. a constrained cruise level), or may even be part of its aeronautical database (e.g. routes, SIDs). Such constraints are derived by the aircraft operator from contextual information available through Aeronautical Information Services (AIS). Other constraints will be entered by the pilot following R/T instructions[3] from an Air Traffic Controller.

The specific impact that a certain constraint can have on a trajectory should be described by the following elements: the dimension(s) affected, the scope in space and/or time of the constraint

[2] The guidance by the FMS is nowadays often limited to three of the four dimensions (i.e. 3D position). In some cases, an FMS can also perform guidance to be at one position at a given time (called 3½D). Future FMSes are expected to be capable of continuous 4D guidance.)

[3] As described in section 2.5 data-link will allow controllers in the future also to send constraints to aircraft. The pilot may not have to enter these in the FMS since the FMS can receive the information directly via the data-link.

(locus and range, [per dimension]), the point where the effect will start and end (this may be different from the range of the constraint itself) and the bounds[4] of the constraint.

Let's have a look at some examples.

Example 1: An ATFM departure slot constraint

An ATFM departure slot constraint is a simple limitation on the departure time of an aircraft. A slot will give a flight a period of 15 minutes, in which the scheduled departure must fall and in which the actual departure should take place.

The only trajectory dimension immediately affected by this constraint is time. The time locus of the constraint is exactly on the planned time of departure and geographically at the departure airport. Its range in time is thus zero and its bounds are 15 minutes around a specific time. The effect of the constraint will start before pushback and the will last till the end of the flight. The range of the effect is thus much larger than that of the constraint itself.

This type of constraint is applied to individual flight plans well before take-off. If the flight departs within the assigned slot the constraint is fulfilled and no longer needs to be taken into account. If on the other hand the aircraft does not take-off within the assigned slot time the further effect of the constraint is that take-off is not allowed until a new slot is assigned.

Example 2: Runway in Use

The departure runway assignment based on the runway in use is a constraint that determines where the airborne trajectory will start. It will thus directly affect the lateral dimensions of the (first part of the) trajectory. The lateral locus of this constraint is the runway location and its lateral range covers the length of the runway. The effect of this constraint may start shortly after begin of taxiing (since the taxi path must lead to the begin of the runway). The constraint also has an indirect effect on the initial part of the trajectory, up to the SID exit point.

Example 3: Standard Instrument Departure (SID)

A Standard Instrument Departure procedure is actually composed of a set of constraints that aims to define a mostly standard departure route and profile. It typically consists of a number of lateral turn instructions, often complemented by level constraints. SIDs are defined as part of the design of the airspace around a particular airport, independently of any specific flight.

A SID will constrain the lateral and vertical dimensions of the first part of a trajectory after take-off. Each of the constraints of which a SID is composed will have its own locus and range. As an example the constraint 'cross at distance x NM from fix YYY at 4000ft or below' impacts the vertical dimension and has its lateral locus on the position determined by the given distance

[4] The bounds of a constraint define the limit values that dimensions of the trajectory should not exceed. These can also be described as a accuracy window around a target value.

from the named fix (and on the route determined by the lateral constraints). The lateral range of the constraint starts at the take-off and is limited to the (unspecified) detection margin for crossing the designated position. The vertical bounds of this constraint are asymmetrical. There is no specific lower bound given (some other constraint may impose one however), and the upper bound is defined as 4000’ft QFE (with a general accuracy level). Since the aircraft is in a climb the effect of this constraint will start at take-off and will last till crossing the given position.

Example 4: LoA - R/T example

Take the example of an LoA (see [10]) that prescribes that traffic with destination ELLX entering the Brussels West Sector via NIK or BROGY shall be co-ordinated so as to cross the Brussels UIR boundary at FL330 or below. For traffic that meets the given conditions this constraint will affect their vertical dimension. The lateral locus of the constraint is either at NIK or at BROGY, depending on the routing of the flight. The lateral range starts at either of the locus points and (implicitly) continues for the remainder of the flight. The vertical bounds of the constraint has an upper limit of FL330 but no explicit lower limit. The effect of the constraint may start some time before its lateral locus, depending on the flight level the flight is coming from.

2.4 Trajectory predictability

For the performance of certain processes in ATM, and particular in ATC, the predictability of trajectories is of significant importance. When looking for example at the primary ATC task of maintaining separation between flights it is clear that in order to guarantee separation at a point in the future, knowledge is necessary of the current position of each aircraft (i.e. the current position on the actual trajectory) and of a predicted trajectory. Another example concerns scheduling aircraft for landing for which knowledge of the predicted trajectories is required.

The operating concept of ATC and the distribution of tasks between human and machine directly impact the predictability of trajectories. The availability of all the required information for predicting the trajectory of a particular flight is beyond doubt essential, but even with the information available, the accuracy of this information will also play an important role.

The description below follows a generic operational concept, derived from the way ATC is performed nowadays in most of Europe. Following the schematic presentation of information present in, and exchanged between each part of the system in Figure 2 an attempt is made to explain the various aspects of trajectory predictability. Numbers (e.g. *{3}*) are used in the text to refer to specific numbered boxes in the figure.

Within the ATC / ATM environment various entities are involved in predicting the future trajectory of flights in some way or another.

On board the aircraft, the pilots have their own mental model *{5}* to predict a future trajectory for their aircraft *{6}* (or of other aircraft). Interaction with the onboard avionics, and the trajectory information contained therein *{13}*, will influence their own mental representation. In making their mental prediction, the pilots will use their understanding of applicable constraints *{4}* as one of the inputs. Through the cockpit interface *{10}*, the pilots will manipulate the constraints as known to the avionics *{11}*. Other information that will be used by the avionics concern the predicted meteorological conditions *{18}* and the known aircraft performance (not depicted). The described interactive process will eventually result in a trajectory that the FMS will try to follow *{12}*. The real trajectory *{21}* that will be followed is of course the resultant of the real aircraft performance, the real weather conditions *{20}* and the guidance and control process of the avionics *{12}*.

On the ground, a similar interaction takes place between the air traffic controllers and the ATC systems. For each flight, an ATCO will also use a mental model *{30}* to make a representation of the predicted trajectory *{31}*. His prediction is taking into account, amongst others, his knowledge of applicable constraints *{33}* and his control intentions *{34}*. By using the ATC system HMI *{28}*, the controllers will manipulate the constraints information known to the system *{27}* and receive feedback on the system representation of the predicted trajectory *{24}*.

Interaction between the air and ground currently takes place mainly along two lines. The pilot receives information about constraints on one hand through the AIS service (directly and through the aircraft operator *{2}*, *{1}*) and on the other hand via R/T *{9}* from controllers. There is normally no direct exchange between the avionics and the ATC system.

The predictability of the aircraft trajectory from the perspective of air traffic controllers is related to the match between their own mental representation *{31}* of the aircraft’s future path and the real path that will be followed *{21}*. The controller’s perception of the real trajectory *{32}* is derived from the ATC system information *{25}*, which in turn is based on surveillance *{26}* of the real trajectory. The control that the ATCO has over the trajectory is effectuated via the R/T communications *{9}* with the pilot, who in turn controls the avionics.

A number of observations can be made to complement this description.

1. There is a complex and distributed way to communicate constraints between ATC and aircraft. The consistency between the constraints sets of the various actors is not simply guaranteed.

2. There is a sequence of individual controllers dealing with each flight, each addressing only a part of the full trajectory. There is an overlap in time between one controller controlling the aircraft and a next controller planning the subsequent part of the trajectory. Even spatially, there is a certain overlap.
3. The control instructions (constraints) issued by the ATCO are often open-ended: they do not define how the trajectory will continue in the future (e.g. heading instructions). They also often allow for a wide range of trajectories that comply (e.g. an instruction to reach a certain level by a certain position may be executed in several ways).
4. The open-endedness of controller’s actions and the low predictability of future controller actions by the ATC system make it difficult for the ATC system to accurately predict a trajectory. Consequently, the controller can not improve his own predictions based on system information. Another consequence is that controllers can not plan very long in advance because of the uncertainty about control actions still to be taken by other ATCOs (and himself).

Observations 3 and 4 are considered the most important factors influencing trajectory predictability.

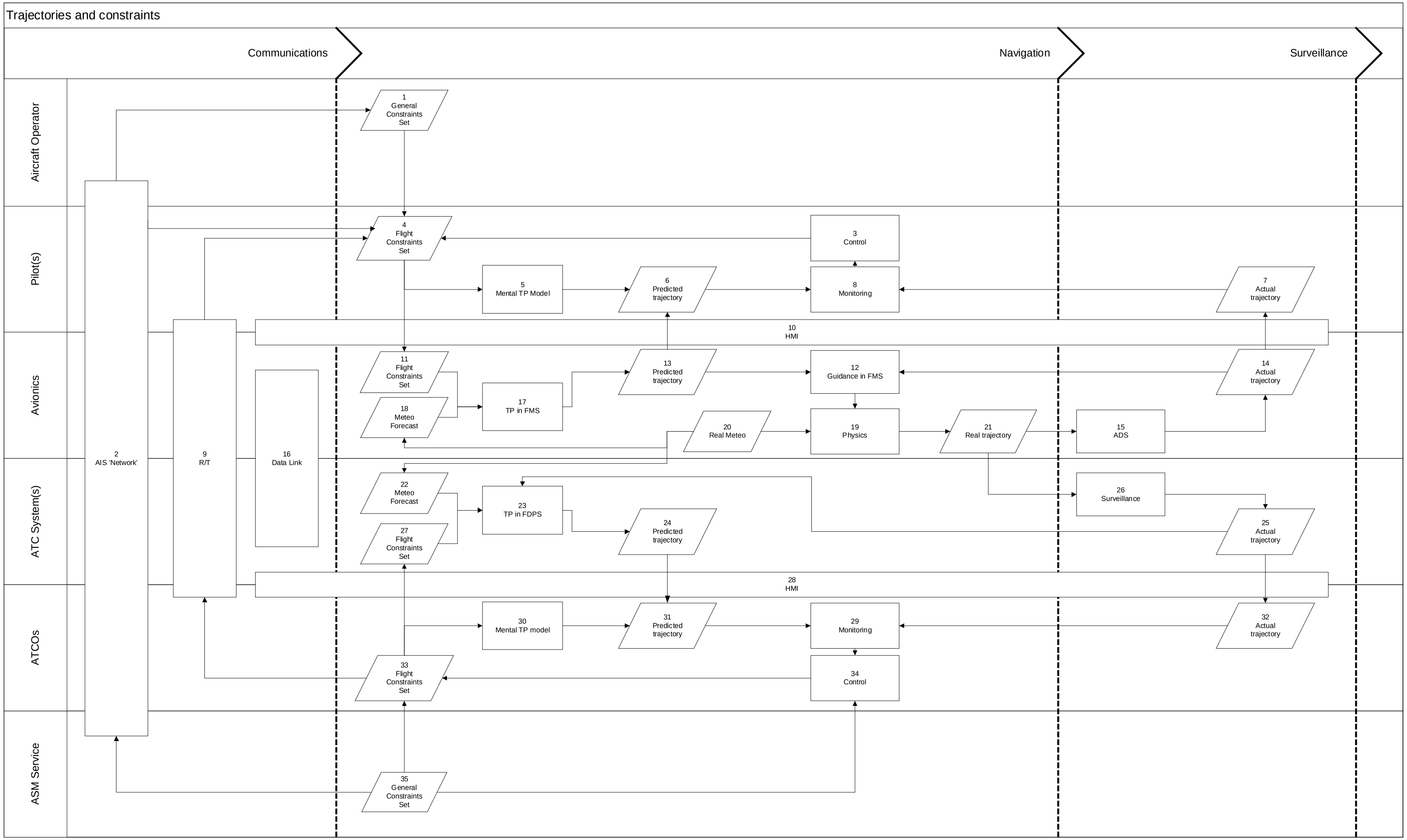

Figure 2: Schematic view of constraints and trajectories from the perspective of various actors.

2.5 Constraints and the development of operational concepts

As described before, constraints are important for the influence that they exercise on the trajectories that aircraft fly. The specific influence very much depends on the concept of operations that is followed. In section 2.4 a description is given of the way in which constraints and trajectories relate to each other in the concept of operations that is currently mostly used. In this section, the focus will lay on the impact that some foreseen operational developments will have on the use of constraints.

In the continuous evolution of ATM, resulting from the need to increase capacity, safety and efficiency in line with the operators needs, there are many new developments. Especially when it comes to capacity and safety, analysis usually indicates a limiting factor in the amount of traffic that individual air traffic controllers can safely handle. Many operational developments are thus aimed at reducing the controller workload per aircraft. Three main solutions are generally envisaged:

1. Share the work between more controllers
2. Increase the support from the ATC system
3. Share the work with the pilots

While the current practice is often to apply solution 1 by increasing the number of sectors, there is a diminishing effect as sectors become increasingly smaller. Future concepts that aim to address the problem differently will be more aimed at solutions 2 and / or 3. Usually these concepts include a changing role and tasks for air traffic controllers (and pilots).

Two mainstream developments will be discussed; *free flight* and ground based *4D ATM*. The latter will be discussed first.

2.5.1 Ground based 4D ATM

The essence of 4D ATM concepts is their focus on an increased reliance on advanced ATC system functions to support the controllers[5]. This is usually accompanied by a redistribution of work between controllers and consequently a changing role for each of them. One of the primary tasks of ATC, providing safe separation between aircraft, is still seen as a responsibility of ATC.

One of the main challenges in providing more automation support to air traffic controllers is to match the functionality and its interface with the controllers tasks and cognitive processing. Figure 3 presents an extended version of Figure 2 incorporating the changes that could result from the introduction of a 4D ATM concept. Just like in Figure 2 both the controller (box *{30}*) and the ATC system (box *{23}*) will have a model for predicting aircraft trajectories.

[5] The description in this section is largely derived from the authors knowledge of 4D ATM concepts gained by participation in the PHARE programme.

Consistency between both models and their inputs is essential for effective system support. When taking the 4D ATM concept as developed within PHARE Demonstration 3 as an example, the ATC system always works on a complete 4D trajectory description for each flight. For each trajectory, there is an associated set of constraints. Advanced human machine interface functionality[6] allows the controllers to manipulate the set of constraints related to a flight interactively. The Trajectory Generator in the system will regenerate a trajectory based on the modified constraints, providing the controller with immediate feedback of his constraint modifications. Considering the availability of an appropriate HMI, the controller and the ATC system will thus share the same view of the aircraft's trajectory. Data-link *{16}* is used to co-ordinate the trajectory and constraint changes with the aircraft. The set of constraints used in the ATC system is up-linked to the aircraft. With this information the FMS is capable of generating a matching trajectory. Just like the controller, the pilot is able to manipulate the constraint list to adjust the trajectory to his preferences. The resultant trajectory is finally down-linked to the ATC system. It is this down-linked trajectory that will be agreed in the end. Consequently all actors have the same view on the trajectory that the aircraft will fly. By means of ground-ground co-ordination also all controllers that will deal with this flight have access to the same trajectory.
With the availability of a trajectory that accurately matches what the aircraft will do for the remainder of its flight, advanced decision support tools can be introduced to support the controllers in their tasks. Monitoring of flight progress compared to the planned trajectory *{29}* can be performed by a Flight Path Monitoring Tool (FPM). Detection of medium term 'planning' conflicts (app. 3 to 20 minutes into the future) can be supported by a Medium Term Conflict Detection tool (MTCD). As a result controllers will have to apply less control actions *{34}* that modify the trajectory. This means that the stability of the future traffic situation will increase.

As will be discussed further in section 2.6 the introduction of this kind of concept will require careful thinking about the system capabilities that will be required by controllers and pilots to interactively manipulate trajectories and constraints. This new form of interaction should eliminate all open-ended instructions and allow controllers full control over the trajectory.

When looking at the trajectory predictability of this concept compared to today's (see section 2.4) the following conclusions seem justified:
1. The consistency between the constraints sets of the various actors is better guaranteed.
2. While there still is a sequence of individual controllers dealing with each flight, each will have exactly the same view of the current trajectory.

[6] In PHARE the tool responsible for this advanced functionality was called the Highly Interactive Problem Solver (HIPS).

3. The new way of manipulating constraints and trajectories by the controllers will eliminate in principle all open-ended instructions. There will normally be an one agreed trajectory from the aircraft's current position to its destination.
4. The predictability of the future trajectory is very high. At any time each flight will have a planned and agreed trajectory up to its destination. While future controller actions remain unpredictable, it will be very predictable what the aircraft will do without them. And if there are control actions, they will immediately be translated into a trajectory that represents the new situation.

When considering the impact that this type of concept will have on the constraints put on flights it is expected that:

- The number of constraints can / will decrease.
- The types of constraints will change.
- The freedom to select an optimal flight path will increase in principle but once a selection has been made a close adherence will be expected.
- The need for LoAs and other procedural constraints will decrease.

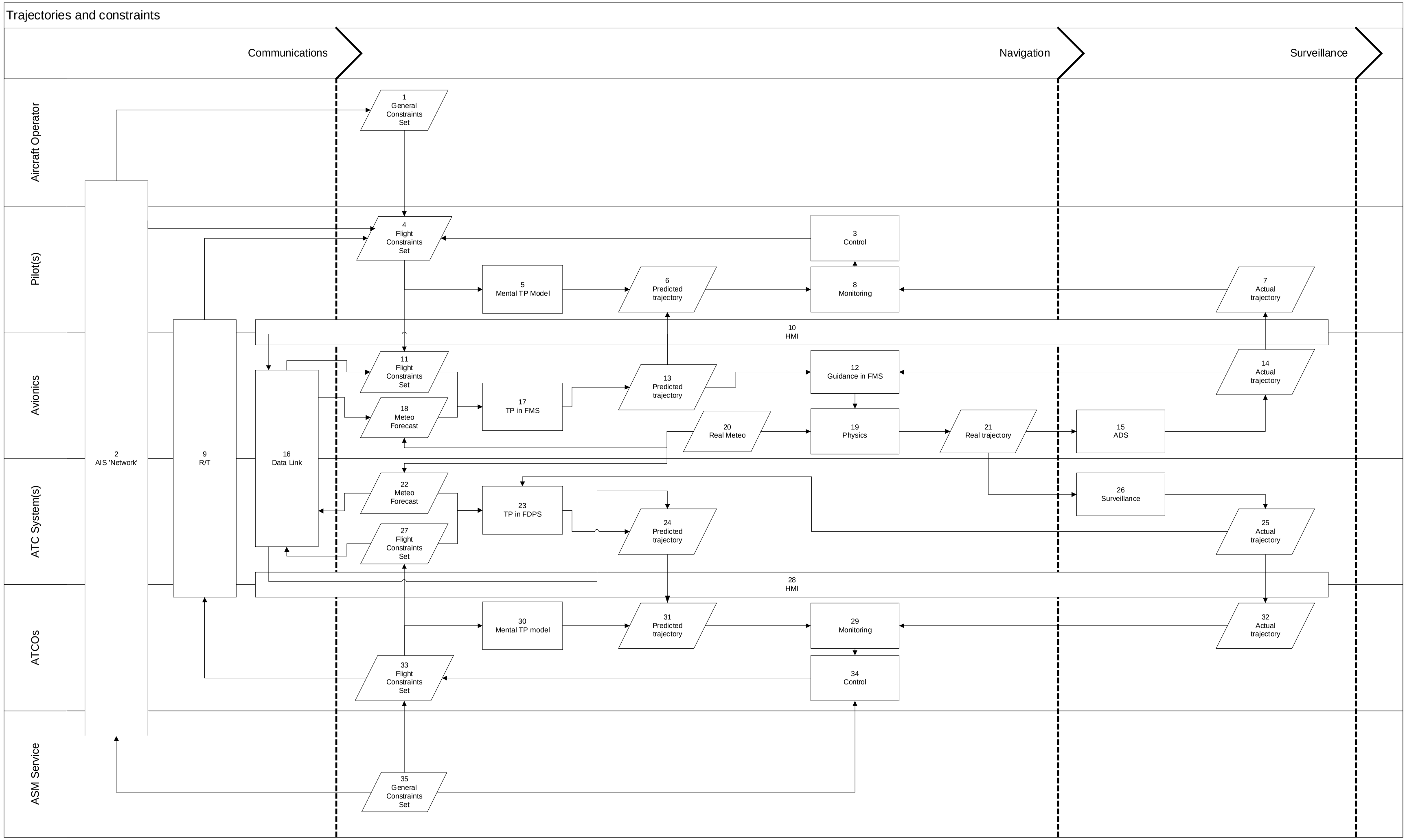

Figure 3: Schematic view of constraints and trajectories in a 4D ATM concept.

2.5.2 Free Flight

The following text box illustrates two essential parts of the definition of the free flight concept as presented in [13] when considering constraints.

> "Free flight" is defined as :
> A safe and efficient flight operating capability under instrument flight rules (IFR) in which the operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. *Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move towards free flight.*
> …..
> In the free flight system, a flight plan will be available to the air traffic service provider to assist flow management, but will no longer be the basis for separation. It is possible, and highly desirable, to shift from a concept of strategic (flight path based) separation to one of tactical (position and velocity vector based) separation. There even may be instances included in the system's design where separation assurance shifts to the cockpit.

It is clear that this idea particularly addresses the elimination of restrictions (i.e. constraints) perceived as unnecessary. A wide range of concepts can be considered to comply to this idea, even the 4D trajectory based concepts discussed in the previous section. Nevertheless, it is generally considered that free flight implies some level of delegating responsibility for separation assurance to the pilot. In such an environment of tactical separation based on velocity and speed vector, the use of trajectories will have to be put in a completely different view.
One needs to go back firstly to the air space management process to identify the impact of a free flight concept on airspace design. Free flight airspace (FFAS, see [11]) will have its own regime of rules. If operators will have the capability to select their flight path and speed in real time, the route network in FFAS will become obsolete. Whether FFAS should still have conventional sectors is a difficult question to answer. It very much depends on the actual role of the controller. That role also establishes the need for Letters of Agreement and inter-sector co-ordination procedures. However, without a route network there are no fixed sector-boundary

crossing points. Consequently constraints related to LoAs and hand-over procedures will drastically change, if they still exist.

Considering the responsibility for separation assurance rests with the pilot, then the constraining effect of flights on each other will be effectuated in a new way. Pilots will need to have access to the flight path intentions of all traffic that could interfere with their own flight path. This intention information could be very tactical in nature (position and speed vector, as in the definition above, see also [15]) or more strategic (a 4D trajectory of relevant extent, see [14]). These intentions from surrounding aircraft will have to be transmitted by those aircraft, as it should not be expected that the avionics of an aircraft would be capable of predicting the trajectory of other aircraft. This also implies that a pilot can only put additional constraints on his own flight and change his own trajectory. He will however not have to share the information on those constraints with others.

In Figure 4 an attempt has been made to visualise the relationship between trajectories and constraints in a free flight context. When comparing with Figure 2 and Figure 3 the situation appears to be simplified. Most of the relationship with the controller's dealing with constraints and trajectories has disappeared. The changing relationship between pilots of different flights may however not be fully expressed by this figure.

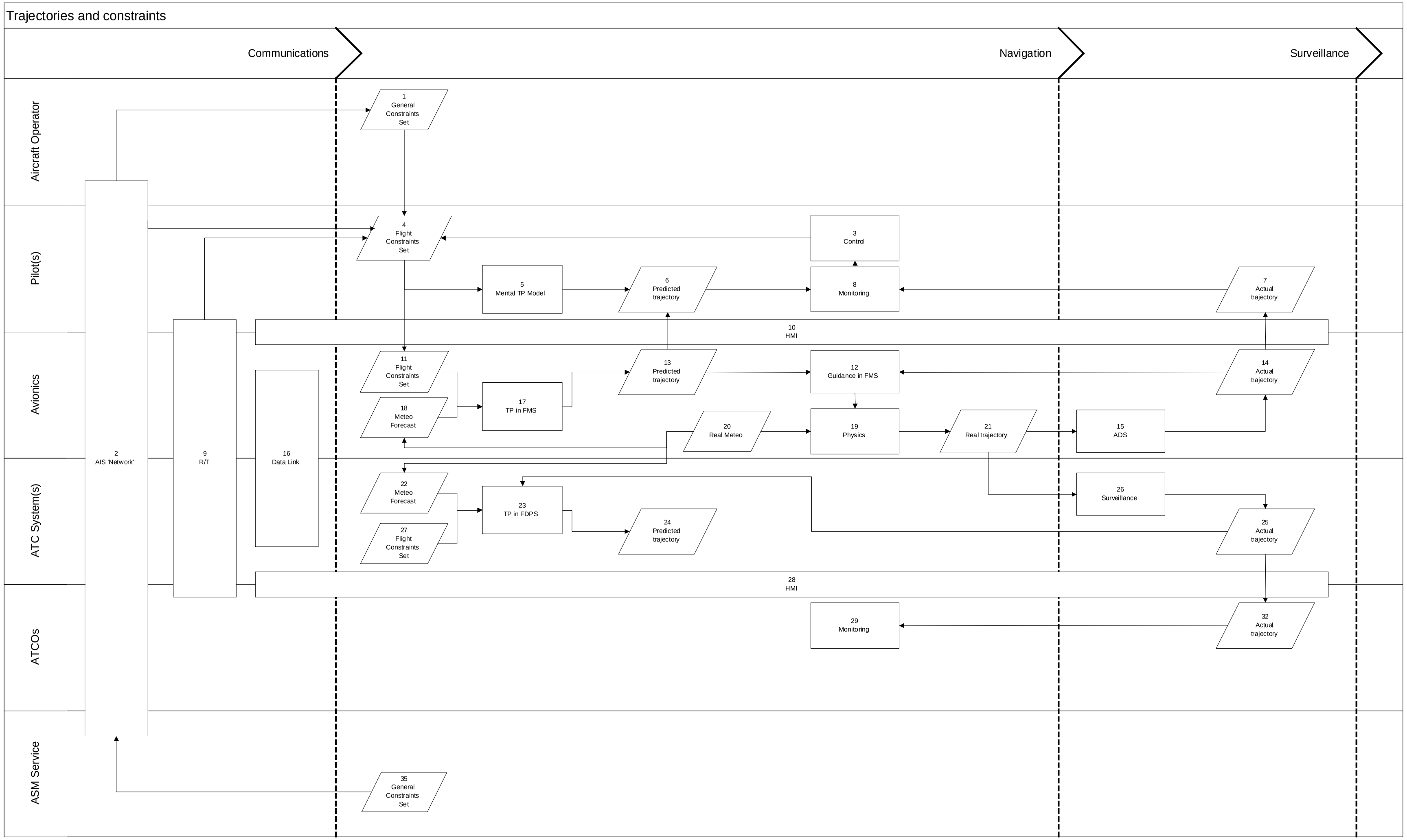

Figure 4: Schematic view of trajectories and constraints in a free flight context

2.6 The human perspective versus the system perspective of constraints

One of the more complex issues related to constraints and trajectories is the interaction between human and machine, either pilot and FMS or controller and ATC system. As presented in Figure 2 both the human and the machine will have their own representation of an aircraft's trajectory. The human's interpretation will be dependent on his knowledge of aircraft performance, flight intentions and applicable constraints. It will however also be influenced by the information that he gets about the flight from the supporting system. The representation of the trajectory in the system will also depend on available information about aircraft performance, flight intentions and applicable constraints. These will however not be exactly the same as those used by the human operator.

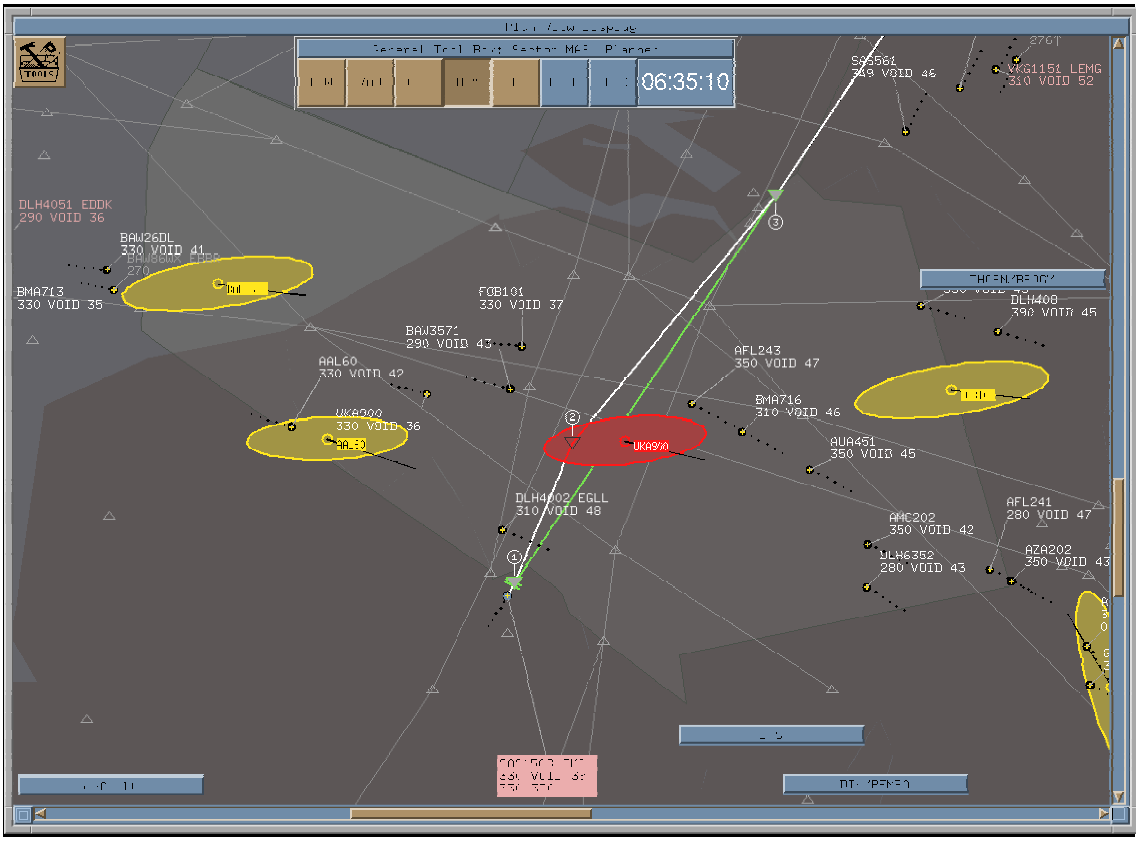

Figure 5: Example HMI for constraint manipulation

The Human Machine Interface (HMI) plays an important role in guaranteeing consistency between the trajectory representations of the human and the machine. It is the mechanism by which the human manipulates information in the machine and usually gets feedback that will manipulate his own representation. In high workload environments, like ATM, the efficiency of the HMI is of crucial importance. The system should thus be able to understand the intentions of the human by correctly interpreting his input orders. These may not necessarily be 100%

explicit. In such a case, advanced technologies, like fuzzy logic and artificial intelligence, may have to be deployed to achieve usable systems.

Regardless of the completeness of the input orders, there is also the problem that these orders may be an indirect means to manipulate something else. As an example of this phenomenon, Figure 5 illustrates a part of the controller HMI of a PD/3 system[7]. The green line extending from the current position of SAS1568 to the top of the picture represents the current trajectory for this flight. The red area indicates a planning conflict with flight UKA900.The white line is the representation of an alternative trajectory that the flight could follow if a constraint were introduced at the place where the black triangle is marked ➁. The controller can manipulate the constraint by moving it to a different position. The system will give feedback by immediately showing the corresponding trajectory. This trajectory is however more than just the white line on the display since there is a lot of information and logic required to calculate it. This can easily fool the human into thinking that he is 'drawing' the trajectory rather than manipulating a constraint.

It may be clear that especially in this area, extensive research will be required to allow for a successful introduction of this kind of concept.

3 Conclusions

This study into a common ATC constraints model for trajectory prediction should be considered as a first step towards achieving a widespread common understanding on this topic. It is not intended to be complete but specifically serves to provide a common starting point and to identify issues for further research and development.

The workshop that was organised on this topic has illustrated that it is not a simple task to get a common understanding on this topic. People will have different views to start with, resulting from their past experience and individual analysis. They will also have different sets of expertise, leading to different interpretations. Nevertheless, the results of the workshop have lead to believe that a more common understanding can be reached and will bring great benefit.

The analysis of current constraints in ATM has indicated that there exists a great variety of constraints for various reasons. These are inherent to the way the ATM process is organised. With new ATM concepts being developed, these constraints will change. It is believed that a thorough understanding of the relationship between constraints and the organisation of the ATM process is essential in the development of these new concepts.

[7] It should be noted that this is an example. It is possibly far from ideal and certainly not as optimised and designed as would be required in an operational system.

4 Recommendations

From the analysis in chapter 2 several issues can be extracted that will need further study. The following list is presenting the most eminent topics. It is probably not complete and certainly not intended to indicate any order of priority.

- The benefits of and need for hand-over procedures and LoAs principally depend on the concept of operations by which ATC service is provided. Quite often, the requirement for specific constraints has historic arguments. In order to judge whether these constraints can be eliminated or reduced an in depth understanding of the operating concept and the local conditions is required. Especially in the development of new concepts the need for this type of constraints needs to be carefully considered.
- When developing advanced controller decision support tools that work on the basis of trajectory information significant research will be required to understand the human cognitive processing of trajectories and the best way to enhance that by automation. The same applies to avionics in direct support of the pilots.
- It is very likely that controllers and pilots will need advanced ways of manipulating constraints in their supporting systems. It can be expected that these constraints will be different than the R/T phrases that are used today. Research will however be needed to find out which types of constraints will be required for controllers and pilots to perform their tasks.
- When airborne and ground systems will be integrated by the exchange of trajectories and constraints it will become essential that there is consistency in the information that is exchanged. International standards will therefore need to be developed for the exchange of this type of information between different ATC systems, between ATC systems and aircraft avionics and possibly between avionics of different aircraft.
- It is however not only the exchange of trajectories and constraints that needs to be standardised. Some means has to be found for ensuring that with a given constraint set (and additional context information) both ATC systems and avionics will generate more or less the same trajectory. This requirement follows from the need for controllers to be able to interactively manipulate constraints and see the effect on a trajectory. As it is unlikely that data-link bandwidth will allow the controller to use trajectory information generated by the FMS interactively, the ATC system will need the capability to predict the trajectory that the FMS would generate. Experience from the PHARE programme has shown that this is not trivial as long as the constraint set does not unambiguously define a single trajectory (e.g. [5],[6],[7]).

5 References

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6 Glossary

AIS	Aeronautical Information Service
ASM	Airspace Management
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
EEC	EUROCONTROL Experimental Centre
EFMS	Experimental Flight Management System
ESCAPE	Eurocontrol Simulation Capability And Platform for Experimentation
FFAS	Free Flight Air Space
FMS	Flight Management System
FPM	Flight Path Monitor
HIPS	Highly Interactive Problem Solver
HMI	Human Machine Interface
LoA	Letter of Agreement
MTCD	Medium Term Conflict Detection
NLR	National Aerospace Laboratory (The Netherlands)
PATS	PHARE Advanced Tools
PD/3	PHARE Demonstration 3
PHARE	Programme for Harmonised ATM Research in EUROCONTROL
TP	Trajectory Predictor

Appendix A ATC Constraints Workshop

A.1 Introduction and structure

In the following sections a summary is provided of what was discussed at the workshop. No attempt has been made in these sections to interpret or further develop what was said at the workshop, other than providing some brief conclusions on the various topics discussed. The interpretation of the workshop results has been presented in the main text of this document.

The structure of this appendix starts off with an overview of the attendance. It then follows the sequence of items discussed at the workshop.

During the workshop, a presentation was given of the work that had been performed by NATS on the topic of EMAN, the En-route Manager. Since it is felt that this presentation was only sideways linked to the subject of the workshop, it has been decided not to cover it in this report of the workshop. It is assumed that details on this presentation can be requested from either NATS or EUROCONTROL Headquarters.

A.2 Workshop attendance

Table B-1 presents an overview of the invited experts, including their expertise, and also shows who actually participated.

Nr.	Invited expert	Background / Unit	Participated
1.	Marc BROCHARD		No
2.	Christopher CHICKEN	EEC	Yes
3.	Daniele CLOAREC	EEC	Yes
4.	Rob EAGLES - NATS	NATS	Yes
5.	Bruno FAVENNEC	EEC	Yes
6.	Mary FLYNN	EEC	Yes
7.	Pierre-Yves GAUTHIER	EEC	Yes
8.	Robert GRAHAM	EEC	Yes
9.	Eric HOFFMAN	EEC	No
10.	Diarmuid HOULIHAN	EEC	No
11.	Volker HUCK	EHQ	No
12.	Anthony INARD	EEC	No
13.	Poul JORGENSEN	EHQ	Yes
14.	Seppo KAUPPINEN	EHQ	Yes
15.	Barry KIRWAN	EEC	No

16.	Rod MCGREGOR	EEC	No
17.	Colin MECKIFF	EEC	Yes
18.	Mike MOORE	EHQ DIS/ATD	Yes
19.	Isabelle PICHANCOURT	EEC (Thales contractor)	Yes
20.	Jose ROCA	EHQ DIS/ATD	Yes
21.	Peter SLINGERLAND	EEC	Yes
22.	Colin SMITH - NATS	NATS	Yes
23.	Lars STRIDSMAN	EHQ DIS/ATD	Yes
24.	Jean-Paul ZABKA	EEC/OPS	Yes
25.	Peter MARTIN	EEC (AVALON), replacing V. HUCK.	Yes
26.	Wim POST	NLR - ATM Concepts expert	Yes

Table B-1: Participants of the workshop.

A.3 Workshop objectives

At the workshop is was presented that the objectives where as follows:

- Achieve common understanding of ATC Constraints and their application in trajectory generation.
- Discuss how, when and why ATC Constraints are used.
- Discuss Pilot / Controller perspectives.
- Identify the impact of concept developments over the next 10 years.

A.4 Setting the scope

The scope of the discussions was limited to the following:

- Only flights with a flight plan would be considered.
- The trajectory of a flight would only be considered from take-off till touchdown.
- The airspace under consideration would not be ‘uncontrolled airspace’. In ATM2000+ terms, this would mean Free Flight Air Space (FFAS) and Managed Airspace (MAS).
- Time-wise the discussion would focus on the way ATM operates now and up to 2010.

A.5 What is unconstrained?

The participants had been asked before the workshop to consider a few questions. One of these questions was to describe what a flight without ATC constraints would mean. The responses received before the workshop are listed here followed by the reactions discussed during the workshop:

{1}

In the perfect world a flight without ATC Constraints would be a flight where the pilot/airline operator chooses when to push back, has the shortest taxi possible with immediate takeoff from the most efficient runway, to fly direct at the most efficient flight level and land directly on the runway of his choice with a short taxi to his chosen gate.
In the route structure world, it would be where the pilot/airline flies his Flight Plan at his RFL and where his arrival can be predicted correctly for gate management.

A few items of this definition were debated:

- If something like a 'most efficient runway' exists then any other choice would be the result of some kind of constraint. Normally the combination of wind, aircraft performance and standard aircraft operating procedures will limit the choice of runways on most airports. In case of multiple runways fulfilling these criteria, there could still be an ATC constraint prescribing a particular runway that may not be the 'most efficient one' from the aircraft's perspective.
- 'The most efficient flight level' in itself is also already a constraint. From the aircraft's perspective the optimum flying altitude may not be a particular flight level and may not even be level (considering 'continuous cruise climb' as the ideal optimum).
- The alternative definition involving a route structure lead to the conclusion that the route structure in itself should also be considered a constraint.
- It was mentioned that also the most efficient/desirable speed should be included in this definition.

{2}

A flight without ATC constraints would be a flight for which no ATC service is provided, since the whole purpose of ATC is to constrain flights in order to maintain safety and an expeditious flow of traffic. No ATC constraints does not mean that there would not be constraints imposed on the flight due to surrounding traffic, but in the self-separation world, Pilots would impose the constraints on themselves (and we can not call them ATC constraints then).

Even though maybe somewhat provocative, the idea behind this definition was fully supported. It could even be further extended to cover most elements of Air Traffic Management (as opposed to only ATC). It was added that besides these constraints that result from the management of air traffic there are also 'constraints' with a different origin, like e.g. the aircraft performance envelope, the terrain (as a boundary to airspace) and the airline operators manual.

In preparing for the workshop the following definition had been drafted by the author of this report:

{3}
A flight performed to meet the objectives of the operator without any further limitations set by ASM, ATFM or ATC.

This definition was presented in order to start a discussion that should result in a common view of what an unconstraint flight would be and what the role of ATC was in constraining a flight. In the discussion the following positions where put forward:

- The controllers job is to manage traffic flow, complexity, using the constraints as part of [his] tools.
- Constraints are not by definition static and may be dependent in their effect on the context in which they are applied (e.g. depending on aircraft performance).
- What are missing in this definition are the operator preferences.
- When considering that more than one aircraft are normally flying around, all flights can also put constraints on each other. Normally the ATC service will effectuate these ‘traffic constraints’ in order to maintain safety. This may be different in future concepts, where separation responsibility may be delegated to the aircraft. Such a change will however not necessarily mean that constraints resulting from ATFM and ASM will also disappear.
- It is obvious that the environment is constrained. What we should be looking at is what the attributes are of an *overly constrained* ATC environment because those are the areas where there are potential improvements. Some constraints will be hard, some will be softer.

Although probably in need of some further refinement, the following definition of a flight without ATC constraints was put on the flip-over in the end:
A flight performed to meet the objectives of the operator in his preferred way without any further limitations set by ASM, ATFM or ATC (it may still be subject to other limitations / constraints like aircraft performance and other traffic).

A.6 What does the flight plan say about ‘intentions’?

Continuing with the agenda the next item was to see which information the flight plan gives about the intentions of an operator to perform a particular flight. The idea behind discussing this item was that the flight plan might not be reflecting the true preferences of the operator because he has already taken some (ATC) constraints into account. It would thus be useful to know what these constraints could be and what effect they may have.
The following items were summarised as expressing the operators intentions through the flight plan:

- Aircraft type
- Departure airport
- Departure time

- Route
- Levels along route
- Speed (when in level flight)
- Destination airport
- Alternate destination(s)

It was discussed that the combination of Departure, Destination airport and Route, together with the aircraft type is also relevant for the trajectory that will be flown. In practice, a long haul flight with a certain aircraft type will show a different (climb) performance than a short haul flight.
The speed information in the flight plan was discussed as being only indicative of the preferred speed when in level flight.

It was generally agreed that the flight plan information was only a limited representation of the true flight intentions of the operator. Not only is it strongly limited in the details of the intended trajectory, a number of anticipated constraints (sometimes hard, sometimes softer) has already been incorporated by the operator. As such the flight plan is not a true representation of his flight intentions.
It was suggested that it might be quite an improvement if the operator would file his detailed planned trajectory as the plan. Another alternative that was suggested was that the operator just indicates that he wants to perform a flight form A to B at a certain time. No other information would be required when performing this plan in ‘free-flight’.

It could be concluded that a good overview exists of which operator preferences are present in the filed flight plan and how they provide only a limited representation of the flight that will be performed. This representation may even be different already from the true preferences of the operator because he has taken some constraints into account already.

A.7 Which ATC constraints can be found in the AIP?

A question that had been asked to the participants in preparing for the workshop was to identify from any national Aeronautical Information Publication (AIP) which ATC constraints could be found there. No input was received on this question before the meeting. With several participants being former air traffic controllers this did not prove to be a problem.
The participants were asked to take a few minutes to write down their own list of AIP related constraints. This information was then collected and summarised on the flip-over. The following list resulted:

- Airspace

  - Sectorisation
  - Routes + Conditional Routes
  - Reserved Airspace
  - Airspace Classes (altitude)
  - Procedures
    - SIDs
    - STARs
    - Holdings
    - Approach
    - Noise abatement
    - Radio failure
- Terrain
  - Obstacles
  - Minimum Safe Altitude (MSA)
- Airport
  - Level
  - Availability
  - Runways
- Speed restrictions
- Level restrictions
- Oceanic route structure
- Traffic Orientation Scheme (TOS)/ Standard Routing Scheme (SRS)/ Route Availability Document (RAD)
- Time availability
- Avionics Capability Requirements
- Ground equipment
- Diplomatic Clearance
- [Weather forecast
  - Wind]
- [LOA]
- [frequencies]

When discussing the topic of ATC constraints expressed through the AIP, it was suggested that the whole AIP is in fact one extensive description of constraints. The AIP is setting the scope in which each flight can be performed. It was argued however that not everything in the AIP has the same direct impact on the actual trajectory that a particular flight will follow.
In particular, issues like customs service availability or even local bus transportation (quite critical in some Mediterranean airports [as recently demonstrated on the Baleares, editorial

note]) were mentioned but considered too remotely connected to a common ATC constraints model for trajectory generation.
Letters of Agreement (LoAs) were also mentioned, but it was concluded that they normally do not appear in AIPs. They do affect the way in which traffic is transferred from one sector/centre to the other and as such can act as constraints.

It could be concluded that a reasonable, generic, overview of AIP related constraints has been generated.

A.8 Which constraints can result from the use of R/T?

A further question, which had been raised with the participants in preparing for the meeting, was to consider the elements of R/T phraseology (ICAO DOC 4444) that can be considered to imply ATC constraints. It was explained that whereas the constraints expressed in the AIPs are more of static nature, those resulting from the use of R/T are more dynamic.

The discussion touched upon the following issues:

- Do we need to quantify the impact that a constraint can have on the trajectory? Or will it be necessary to prioritise constraints
- All R/T clearances can be categorised by the following three types:
  - Immediate
  - Conditional
  - Target
- Clearances can be given to constrain the following ‘attributes’:
  - Heading (Route)
  - Level
  - Speed
  - Time
- In theory a large number of combinations (several hundreds) are possible when combining a certain type of clearance with a certain constrained attribute. In practice however, only few are frequently used.
- Clearances can also indirectly lead to a constraint, e.g. in the case of weather information.
- R/T instructions can be ‘open’ or ‘closed’. An ‘open’ instruction will constrain one or more of the attributes of a trajectory to a certain value but does not give any information on the further development of that trajectory. Without further clearances, the flight will normally not return to a trajectory that meets the operators objectives. A ‘closed’ instruction will make a flight deviate temporarily from its expected trajectory, but will bring it back to that at a certain point / time in the future.

- In a particular sense, a departure clearance is imposing a constraint on the trajectory, both when given and when not yet given.
- R/T is in fact no more than a delivery mechanism for the air traffic controller to get his instructions to the aircraft. From the mental picture that the controller has about how the traffic situation should evolve, one or more R/T instructions are generated that aim to achieve the desired situation. These instructions however do not explicitly define that situation but manipulate certain attributes in such a way that the desired situation should develop [this is a somewhat edited summary of part of the discussion, which in itself was probably less explicit on this topic].
- Some confusion arose when it was felt by one of the participants that R/T phraseology was looked upon as constraining the controller in achieving his plan of actions. It was tried to explain that the objective was to identify the particular constraining / controlling capabilities that are given by R/T to a controller for achieving his plan.
- In addition, some confusion was noted with several participants that appeared to be directed in their view of ‘ATC constraints’ by the way this term is currently used in the ESCAPE system. In trying to overcome this confusion it was found that the current implementation is actually aiming to represent a very basic ATC system without any decision support tools or advanced trajectory modelling. ATC constraints are used in some way to deliver the proper sector sequence and the main problem is how controller inputs can be translated into profile computations. An additional problem is that the controllers often do not input all their R/T instructions in the system. Since it is anticipated that in the future possibly different instructions may be used, or they may be delivered differently, the expectation of this workshop for these participants is to provide answers about these possible developments.
- It might be interesting to identify if a survey has ever been made of the frequency of use of various R/T communications (of course it was immediately put forward that the ‘hello’ and ‘goodbye’ contacts would be at the top of the list).

It could be concluded that the possibilities for ‘constraining’ a flight by the use of R/T are sheer endless. R/T instructions can nevertheless be classified in certain types and can be related to the various dimensions (route, level, …) of a flight.

A.9 How do constraints and preferences result in a trajectory?

Having identified in broad term the constraints coming from the AIP and from controller instructions and having looked at the preferences of the aircraft operator the next topic for discussion was to see if it could be identified whether certain rules/regularities exist for when particular constraints dominate and thus shape the trajectory.

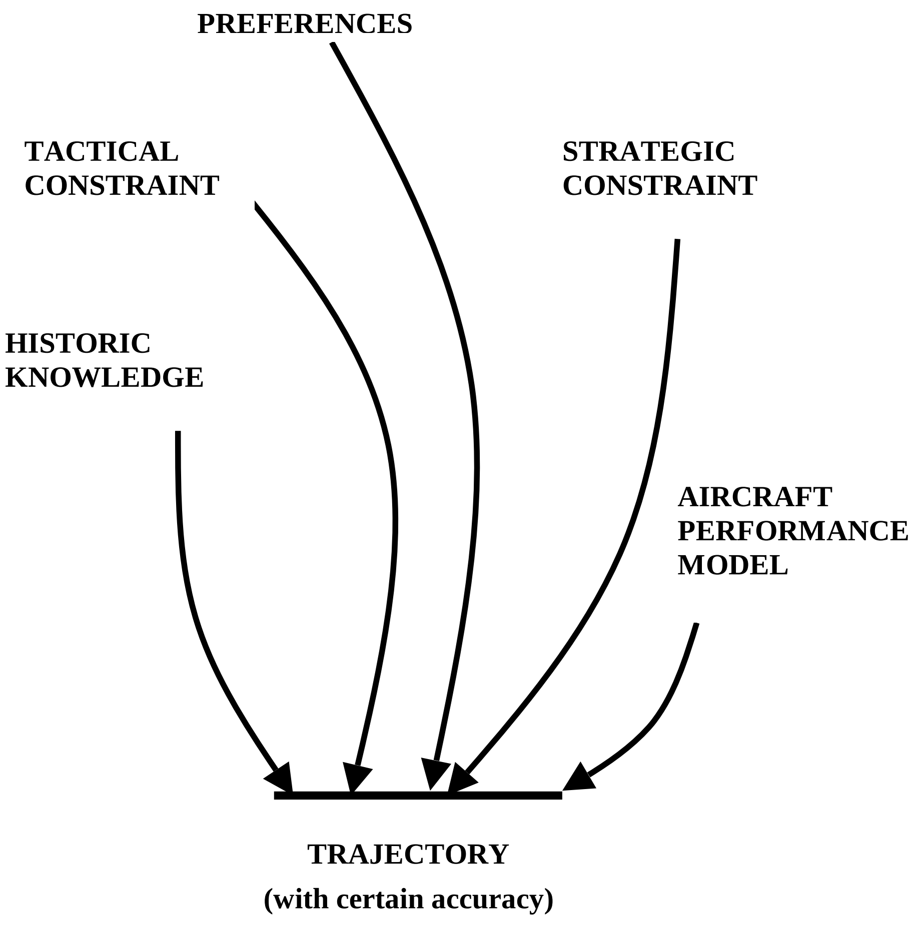
It had also been asked before the workshop that participants consider what inputs would be required to be able to predict the trajectory of a flight. In addition, the role of ATC constraints in this process was asked for and whether there would be a way of telling which constraint would be dominant at which moment. One description was received before the meeting concerning the trajectory modelling and handling from a perspective of working with (fewer) constraints. Due to its length, the reaction is included in an endnote.[i]

The discussion at the workshop addressed the following issues:

- Constraints regularly affect only one or two dimensions of the trajectory. While a level constraint will influence the vertical position of the aircraft, it will normally not influence its route.
- Over the lifecycle of the flight, ATC constraints have different influences. Before take-off, only the AIP related constraints will influence the foreseen trajectory of the flight. Once airborne, constraints resulting from R/T instructions will start to have their effect. Then it may become a problem for a system to know the priority of various constraints.
- Will the constraints lead to one unambiguous trajectory? This will normally not be the case. From the controller's perspective the problem is however not one of ambiguity but one of uncertainty. A controller will know what flights are expected to do in a certain situation. Yet he will not precisely know what the flight will do. When you start building advanced ATC systems with Decision Support Tools, these tools will also need to work with accurate trajectories. As long as trajectories are not accurate these tools will also need to have knowledge about the accuracy of these trajectories.
- When trying to construct trajectories there are two major sources of error.
    - There are inaccuracies in the aircraft / operator performance models that are being used.
    - Future ATC constraints resulting from controller R/T instructions can hardly be predicted.
- There is a certain amount of flexibility for air traffic controllers to follow the 'strategic' or static constraints or not. Especially deviations from the Letters of Agreement can easily be negotiated. Deviating from e.g. AIP related constraints is also possible at the discretion of the controller since he is knowingly responsible for what happens in his sector. Strategic constraints are there to provide a basic safety margin in the system. Controllers know that they can break many constraints but can still recover the situation. The safety margin will be eroded however.
- It was considered 'absolutely stupid' that in European ATC systems we allow plus or minus three minutes differences on a co-ordinated entry/exit time while all times are calculated with high accuracy.

It is concluded that it is not simple or straightforward to identify how operator preferences, strategic and tactical ATC constraints in the end lead to a trajectory that will be flown. It is clear that in current systems there is a fair amount of uncertainty about the predicted trajectory, yet there is also a tendency to require more and more accurate information about a flight's future 4D position. The result is depicted in the following figure:

An overview of the various aspects of ATC constraints as discussed during the meeting is presented in the following table. A few items have not been discussed in detail during the workshop but have been added by the author on the basis of the other work of this study.



True flight preferences	Operator schedule	FPL flight objectives	Unconstrained flight	Strategic constraints	ATFM Constraints	Tactical constraints
		Aircraft type	A flight performed to meet the objectives of the operator in his preferred way without any further limitations set by ASM, ATFM or ATC (it may still be subject to other limitations / constraints like aircraft performance and other traffic)	Avionics Capability Requirements Diplomatic Clearance		
Preferred runway		Departure airport		Airport ▪ Level ▪ Availability ▪ Runways		[Runway assignment] Departure clearance
	Schedule of all flights	Departure time		Time availability	Departure slot	Take-off clearance
Ideal route Route alternatives		Route		(Conditional) Routes Route availability Reserved Airspace Airspace Classes Procedures – SIDs – STARs – Holdings – Approach – Noise abatement – Radio failure Ground equipment [LOA]		Heading / Route instructions
Optimum level		Levels along route		Level restrictions Terrain ▪ Obstacles ▪ MSA		Level instructions
Optimum speed Cost Index		Speed (in level flight)		Speed restrictions		Speed instructions Time instructions
Preferred runway Landing time prefs.		Destination airport Alternate destination		Airport ▪ Level ▪ Availability ▪ Runways		Approach clearance Landing clearance

A.10 What could be the impact of future concepts?

The final question which had been asked to the participants in preparing for the meeting was to consider what the possible impact could be of foreseen developments in operational concepts in the medium term future. This was also the last item on the agenda of the workshop.
The idea behind this question was to identify whether the scope of constraints, their definition, their use and their impact on flight trajectories is expected to change in the coming decade.

The first reaction on this topic addressed the reason for the developing concepts, being e.g. a target increase in capacity or more freedom (i.e. less constraints) for aircraft that would allow to increase the efficiency [editorial note: this question should not necessarily be interpreted as indicating that efficiency means less capacity or vice versa]. It was stated that the reasons for changing the concept were not so much important as were the impact on constraints. Another comment was that the operators may not necessarily be looking for more efficiency but for more predictability.
There was some discussion on whether constraints were foreseen to evolve from specifying what to do, to specifying what not to do and thereby allowing the operator more freedom to fulfil his flight preferences. It was generally considered that the number of constraints would gradually be reduced, e.g. because of the introduction of advanced decision support tools, allowing the aircraft operator to clearly define his preferred trajectory. Yet, once defined this trajectory would become a relatively strict constraint (until redefined). In this development the trajectory information coming from the aircraft is considered very important since it is what the aircraft will be constrained to. Its accuracy is expected to be far greater than the current predictions in the ATC systems. The discussion referred to experience from PHARE and FREER trials. In PHARE the Highly Interactive Problem Solver (HIPS) tool was used to generate coloured areas on the ATCO display to indicate areas where a flight would get into conflict (or close to a conflict) with other flights. The ATCO would design his constraints (lateral, vertical or in speed/time) to as to keep the aircraft free form this other traffic. The ATCO was actually designing the required trajectory rather than specifying the freedom for the aircraft to design its own trajectory. In one of the FREER trials this was changed to give the pilot directly the coloured areas on his NAV display so that the pilot could design his trajectory avoiding them. The role of the controller in this context was briefly discussed. It was generally agreed however that the role of the controller is going to change and with this change will come a change in ATC constraints. The introduction of Decision Support Tools like AMAN, DMAN, CORA etceteras will also influence these changes and with these tools come new ways for controllers to manipulate constraints while interfacing with the system. Especially with the introduction of data-link will the capabilities to communicate constraints from controller to pilot change drastically. The types of constraints are expected to change significantly when controllers and tools actually start working with (4D) trajectories.

A change to airborne separation assurance responsibility would eliminate many ATC constraints but would force pilots to deal with air traffic constraints themselves.
As described before, it was felt that the number of [strategic] constraints would reduce, and constraints would become more dynamic [i.e. tactical]. Together with the introduction of new system interfaces this may make it possible for controllers to apply rather more and/or stricter constraints. Similar effects have been noted with the introduction of other changes (like SYSCO).

In conclusion it may be stated that there was general agreement that ATC constraints will evolve with the introduction of new concepts. They will probably reduce in number, become more dynamic, and may lead to a stricter enforcement of the preferred trajectory.

A.11 Review of workshop objectives

After discussing all items on the agenda of the workshop the objectives as stated at the beginning were reviewed to assess whether they had been met. These objectives were:

- Achieve common understanding of ATC Constraints and their application in trajectory generation.
- Discuss how, when and why ATC Constraints are used.
- Discuss Pilot / Controller perspectives.
- Identify the impact of concept developments over the next 10 years.

On the first objective all participants were asked to express their opinion on whether this had been achieved. These opinions are summarised as follows:

- The scope of the discussion probably covered more than only ATC constraints. Several items were discussed that should probably not be considered ATC constraints.
- ‘*It is now more confusing than at the beginning*’
- There was some worry that ATC will now be considered a constraint (this implicitly referred back to the statement at the beginning that a flight without constraints would be a flight not subject to ATC service). It was argued however that this was not necessarily a negative view since ATC service provision has the purpose of providing safety and does so by applying constraints where necessary.
- This lead to the statement that not all ATC constraints are by definition good. Many constraints, especially the strategic ones, could be considered superfluous. Many of these strategic constraints are however linked to institutional issues. When they are improved, [strategic] ATC constraints will reduce as a consequence.
- It was felt that the discussion was too much ATC oriented. It was answered that the second item on the agenda had been to discuss the preferences as expressed by the operator in the flight plan. Also later on it had been discussed what the balance is between operator

preferences and constraints. Nevertheless it was felt that more input from an airborne perspective would have been welcome. Unfortunately, some people working in this field that had been invited had not attended the workshop.

- If ATC constraints reduce there may be more room for operators to express their real preferences. The question will then be whether the full capabilities to support such communications exist. This is already found a problem in current CDM activities.
- It was put forward that an item which had not very much been addressed at the workshop concerned the accuracy with which a constraint had to be met. Currently several default rules exist for the accuracy with which e.g. a route (RNAV) or level constraint (level accuracy) should be met. One area which is still under development is vertical performance (VNAV). It seems that even the aircraft manufacturers know that the way their aircraft fly does not always come to the benefit of predictability. These considerations about accuracy will mainly affect the tools to be introduced since the controllers should not be bothered by such details.

It should probably concluded that at least all participant will now suffer from the same confusion on this topic.

The second objective was discussed quite extensively in several agenda items whereas the third objective probably received somewhat less attention. The final objective to discuss the developments over the next decade was again covered to a good level in the last agenda item.

All participants were asked to give their final conclusion about the workshop, which lead to these statements:

- *I think that less constraint on the controller or the pilot, will imply more accuracy on the trajectory and it won't be easy to solve this kind of problems*
- *There is a lot of stuff we haven't answer today. [Someone] for example, was asking about changing controller roles, different kinds of constraints, etc. There is significant potential for further and probably a more structured approach to discussion on constraints. What you have to do is to go outside this circle of people; […] If you want to discuss a pilot perspective, you get a pilot to present that; if you are going into trajectory generation, get somebody who's doing that, probably even from the industry*
- *One of the reasons that we proposed this workshop was that we are talking about these constraints a lot and it seems, at least to me, that we are sort of speaking about the same thing, but not really the same thing and today has clearly indicated that. For me, it was useful and I don't think it should be left at this. The report that's coming out of it is going to be quite crucial. Such aspects as the last one should be pursued. I think that a good*

definition for the ATC constraints, would be something like: ATC constraints define the free space within which an aircraft can deviate safely from its agreed trajectory.

- *My expectation for today I'd suppose, was to get a clear understanding of what other people thought ATC constraints were. I am a bit disappointed that there were no pilots or AOC representatives. However, with all the discussion we had on what ATC constraints were, it did broaden my understanding. I've been working in the FDPS for quite sometime and I suppose we've only focused on the constraints as we know them: the classic time, level and not about constraints on a vertical gradients or speed gradients. I would like to see more detailed analysis.*
- *There were a few hints of the possible future types of constraints that we can expect. From my point of view we would like to see a much more concrete definition of the type of things that are required.*
- *I just would like to add support. We should try that there will be a follow-on, we definitely want to have some industry and pilots and AOCs here. Otherwise, it's not too interesting.*
- *I agree with that as well. When I came in this morning I had no idea of what we were going to talk about; I didn't expect that we would find any solution or any real conclusion. What is for sure is that all the talk we had is just a beginning. The group must be wider. I didn't expect results, but the result is that the discussion is open. We have to live for quite a while with constraints; whatever people think about what constraints really are: rules by air traffic controllers or constraints created just to annoy airline operators. No, I don't think it's like that. Constraints are there and we have to live with them and I think that a lot of other people from other orientations should say a word about that.*
- *In fact, I have had some specific issue in mind from the trajectory point of view so, in fact, I expect further discussion to be able to explain why, when a controller would like to input some constraints to define a trajectory, the system could accept all these constraints*
- *At the end of this workshop I'm quite convinced that we don't understand exactly the same thing that's behind the word ATC constraints. When I joined this meeting this morning I had in mind with my experience with simulation, airspace organisation, that ATC constraints was initially a build in, because it linked indirectly for airspace design, but it's because European airspace design is so complex, because the air traffic controller saw that introducing tricks called ATC constraints, let's say to bypass the impossibility to have the proper design of their space, and just because of that. So, I think we don't have all this perception and now I think that the discussion today was more general. I would call it ATM constraints, because we were mixing quite a lot of things. It was very confusing to me. Then, you have this notion which is a trajectory or profile, which is something that's important for ATC constraints but not directly linked. The trajectory can live without ATC*

constraints. I can understand, when you start thinking of the future, we need to introduce new tools for the controller and you need to have the proper trajectory and the proper profile, but I'm not quite sure that the issue is ATC constraints.

- *I always have a bit of aversion to this term constraint, so I was happy to come here to find out what was meant by constraints. I was worried about maybe a nasty shock and something that would change my world, my view of how I see air traffic and air traffic control. But I haven't had any nasty shocks. I was also glad to hear that Boeing are also considering flying aircraft in a more predictable way, because one of our puzzles when we observe how aircraft actually fly, is a nature of that predictability… I'm happy enough; I'm not sure how we can move forward from here.*
- *I find it pretty confusing. I would say the discussion on what are ATC constraints is very interesting and we should perhaps ask the experts of trajectory prediction. We should look at all the different things that go into the trajectory prediction and not only the ATC constraint. I would say that the scope needs to be wider, to get the most from the discussions.*
- *Personally, I don't think I gained so much new knowledge myself, but probably hearing the comments around the table at the end indicate that this workshop has been a very good thing, because it seems that everybody is confused about what a constraint is. So, I'm sure the report might be a good foundation for moving, so eventually we all find out and agree what a constraint is.*

All participants were thanked for their contribution to the workshop.

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[i] The following answer was received in response to the question how constraints and preferences result in a trajectory?

For Trajectory Prediction we need to know where an aircraft is likely to be at a given future time. This can be modelled as a sequence of (lat, lon, alt and time) specified trajectory points. The position of the aircraft at intermediary times is then determined by interpolation. Such a trajectory can be used to represent the most likely future aircraft profile - the mean profile.
However, in spite of our best endeavours the actual profile flown will undoubtedly deviate from the mean profile for a number of reasons.

Although for traffic control purposes we should try to reduce these deviations it is equally important that the size of the likely deviations is known. The simplest scheme would be to augment each trajectory point with a set of tolerances in along-track, cross-track and altitude directions that determines a volume of airspace (a bubble) that moves with time and serves to define a containment volume for the aircraft. At its simplest the bubble could be cuboid or ellipsoid. An ellipsoid would be better for a statistical treatment with the tolerances being statistical variances.

In the present world viewing augmented trajectories as an expression of the statistical spread of future aircraft positions makes sense as it allows for loss of separation probabilities between aircraft to be determined and hence conflict alerting strategies can be developed. With 4-d trajectory negotiation our augmented trajectory looks more like an envelope for the contracted trajectory.

As regards offering areas of airspace in which aircraft may like to choose a trajectory we could see a very tolerant trajectory being composed with the point specific tolerances being relaxed until they approach the contracted trajectories of other aircraft or off-limits airspace.

So we have an augmented trajectory form capable of describing:
· probabilistic trajectories
· contract trajectories
· offered trajectories

Now consider how conflict resolution might work. In order to avoid a conflict between two aircraft, one (it could be both) aircraft will need to manoeuvre by initially either turning left/right, climbing/descending, or increasing/decreasing speed. In order to allow the aircraft complete freedom we could send six offered trajectories the union of which would describe the total space time ATC constraint envelop in which the subject aircraft could choose a solution trajectory for contractual purposes.

The foregoing shows one way of determining and describing the ATC constraint envelope (for separation maintenance) for an aircraft and such an approach would seem reasonable as it is effectively an extension of controller tools currently in development that are centred on the concept of a system trajectory. We will call this the Macaroni approach as it is built up by tubes.

Alternatively we could use the set of all other contracted trajectories together with an explicit definition of off-limits airspace. Such approaches would entail considerably more data being employed to define airspace available to an aircraft. This is rather a departure from current treatment but does offer a little more freedom than the Macaroni approach we call this the Swiss Cheese approach. Note is possible to specify the available airspace with a sparse 4-d matrix whose cells represent quantised regions of airspace-time claimed by other aircraft/organisations.
[..]
It may be necessary to "pinch" offered trajectories due to sequencing constraints. For example an arrival manager will prescribe an arrival time interval (slot) for the approach fix.